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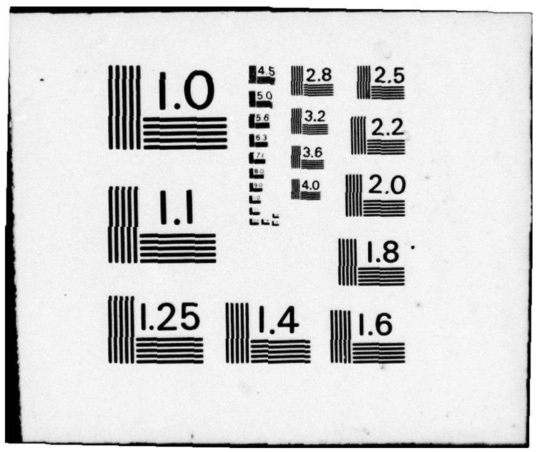
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COLLEGE OF ENGINEERING

NONEQUILIBRIUM EFFECTS IN NOZZLES AND EXHAUST PLUMES

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results of a study of nonequilibrium effects in jet and rocket nozzles and exhaust plumes are presented. The study considered turbulence modeling of axisymmetric compressible jets, particle laden jets and chemical nonequilibrium in axisymmetric jets. It was found that available turbulence models do not correlate a wide range of data for compressible jets. Studies of particle laden jets provided reasonable correlation to experimental data. The chemical nonequilibrium studies suggest a possible explanation for differences between observed and previously predicted radiation behavior of axisymmetric exhaust plumes.

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Abstract

Results of a study of nonequilibrium effects in jet and rocket nozzles and exhaust plumes are presented. The study considered turbulence modeling of axisymmetric compressible jets, particle laden jets and chemical nonequilibrium in axisymmetric jets. It was found that available turbulence models do not correlate a wide range of data for compressible jets. Studies of particle laden jets provided reasonable correlation to experimental data. The chemical nonequilibrium studies suggest a possible explanation for differences between observed and previously predicted radiation behavior of axisymmetric exhaust plumes.

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I. Introduction

The fundamental understanding of exhaust plume characteristics is of considerable practical importance to the United States Air Force. Vehicle detectability depends on exhaust plume radiation, plume radar cross sections affect vulnerability of tactical weapons, and highly expanded afterburning plumes can lead to vehicle contamination effects. The detailed study of these phenomena with full scale vehicles, over the range of vehicle operation is a difficult experimental task. The development of plume prediction models provides an alternative means of determining these phenomena.

A number of codes have been developed (1, 2, 3, 4) which include many of the physical and chemical phenomena in the exhaust plume. These models of exhaust flow may be divided into four categories (4): i) parallel mixing models, ii) uncoupled, underexpanded flow models, iii) limited coupling models and iv) complete coupling models. Under the assumptions of the parallel mixing model radial pressure gradients are considered negligibly small compared to gradients due to turbulent mixing and chemical reactions. The governing equations then take the form of parabolic partial differential equations. In the uncoupled underexpanded flow models the flow is described initially as inviscid and hyperbolic and a method of characteristics solution is employed. Additional calculations are necessary to assess viscous and chemical kinetic effects which can be patched to the above solution. Limited coupling models allow the inclusion of coupling between some of the governing differential equations while neglecting coupling between others. The most general solution represented by complete coupling has recently been developed (3). These models all rely on separate evaluation of chemical kinetic and transport property coefficients as input data.

The study which is reported here is part of an attempt to evaluate input transport phenomena and chemical effects in afterburning exhaust plumes. The first portion of this study focused on the review and an attempt to evaluate turbulence models of compressible axisymmetric homogeneous jets. Since it is known that particles are important in exhaust plumes, the extension of one of these models to include particles in the flow was the next area of the study. Chemical effects were then added to the mixing turbulent jet flow to evaluate the effect of initial mixture composition on the chemical history of the jet. These results are summarized briefly below before presenting the study in more detail in succeeding sections of the report.

Previous experimental and theoretical studies of axisymmetric jet mixing have included compressible and incompressible jets and homogeneous and two phase jets. Homogeneous incompressible jets have been studied most extensively and correlation between experiment and analytical descriptions seems adequate. Homogeneous compressible jets have been considered (6, 7, 8) and some experimental data are available. However, attempts we have made to find a common correlation of these data for example by a single turbulence model, have not been successful. The problem is complicated by very complex shock wave interactions in the near flowfield. However, even a generalized description of the far flowfield seems unavailable at this time.

Available experimental data for two phase jets includes very limited studies on incompressible (9) and compressible (10) jets. These data are generally not sufficient to verify analytical descriptions of the flow since only a limited range of conditions have been studied. Nonetheless, analytical two phase flow solutions have been obtained by limited

solution of the Navier-Stokes Equations (3, 5, 11). In order to describe these flows more accurately, experimental measurements in two phase axisymmetric jets must be made over a wider range of experimental conditions.

The effects of particles in real gas flows are reflected in a number of changes in the flow. In general, particle velocity and temperature may be different from the gas velocity and temperature, the particles may diffuse at different rates in shear layers, and, finally, mass may be exchanged between the particle and the gas. Attempts to account for these effects have led to a number of approximate descriptions of the flow. Particle velocity and temperature have been assumed to be in equilibrium with the gas or frozen at its initial velocity or temperature. The same equilibrium or frozen description has been applied to particle diffusion effects and to phase change or chemical reaction of the particles. These two limiting conditions are most useful as extremes of the real, dynamic interactions between the two phases.

In studies under this grant, an analytical solution procedure was developed for the description of particle flows in shear layers. The model incorporates the dynamics of interaction between particle and gas phase. Governing conservation equations for gas and solid phases are solved by a modification of the integration procedure of Patankar and Spalding (12) for 2D parabolic flow. Analytical results were compared to detailed flow and particle concentration measurements made for jet flow and for duct flow. It was found that the analytical mean solid fluxes in a two-phase jet flow agree well with the experimental results and that the analytical velocity profiles in a two-phase duct flow agree fairly well with the experimental results. The study also considered overall properties of the jet flowfields including spreading rates, entrainment formulae and centerline velocity decay.

A final investigation reported here is a study of the chemistry of afterburning plumes. Chemical reactions in axisymmetric jets similar to jet and rocket exhaust arise from mixing of unburned fuel in the jet with air. The complete description of the flowfield requires knowledge of viscosity and chemical kinetics in the jet. Recent measurements of plume radiation properties (13) and predictions based on calculations of reacting flowfields have not been in agreement. One possible explanation of this discrepancy has been the possibility of a mixture at the nozzle exit with a substantial excess of unburned fuel. Calculations which we made for reacting jets with a nonequilibrium nozzle exit composition qualitatively supported this explanation for the radiation discrepancy but could not quantitatively account for the difference.

II. Turbulence Modeling of Shear Layers

The problem of turbulent mixing of compressible jets with air is complex and many practical data are not available. Although considerable study has been undertaken by other authors of incompressible jets (25) both experimental and analytical study of compressible jets is much less complete. An historical review of turbulence models for axisymmetric jets is presented in Table I. Some of these results will be discussed here with relevance to compressible afterburning jet plumes.

Harsha (23) has critically reviewed many of the turbulence models studied so far and recommends that attempts to modify basic Prendtl eddy viscosity model or the mixing length theory to make them apply to more complex flows is not productive. None of the modifications of the Prendtl eddy viscosity model, including Donaldson and Grey (7) compressibility correction are capable of greatly altering the basic shape of the axial centerline velocity decay curve, and the shape predicted by the Prendtl model and all of its derivatives is incorrect for complex (two-gas) flows. On the other hand, the displacement-thickness model proposed by Schetz (21) is the only locally-dependent model to show the proper behavioral trends for hydrogen-air mixing. Because of this, its use should be investigated in other dissimilar-gas flows. Given some knowledge of the initial turbulent shear stress, the turbulent kinetic energy method (24) is capable of providing better and more uniform predictions over a wider range of flows than any other models investigated. Because of this, it clearly holds the greatest promise for future development.

In order to evaluate the predictive ability of some of these turbulence models, calculations have been made for conditions representative

TABLE I

Eddy Viscosity Models for Main Mixing Region of Jets and Wakes

S. No.	Author/Model	Year	Expression for Eddy Viscosity	Remarks
1	Prendtl	1926	$\epsilon = \ell^2 (\frac{\partial u}{\partial y})$ (Planar, axisymmetric, incompressible)	ℓ proportional to the width of the mixing region.
2	von Karman	1930	$\epsilon = k^2 \frac{(\frac{\partial u}{\partial y})^4}{(\partial^2 u/\partial y^2)^2}$ (Planar, axisymmetric, incompressible)	
3	Taylor	1932	$\epsilon = \ell_\omega^2 (\frac{\partial u}{\partial y})$ (Planar, axisymmetric, incompressible)	$\ell_\omega = \sqrt{2\ell}$
4	Prendtl	1942	$\epsilon = \ell^2 \sqrt{(\frac{\partial u}{\partial y})^2 + \ell_1^2 (\frac{\partial^2 u}{\partial y^2})^2}$ (Planar, axisymmetric, incompressible)	Requires two mixing lengths.
5	Prendtl	1942	$\epsilon = k_1 h (u_{max} - u_{min})$ (Planar, axisymmetric, incompressible)	Introduced "velocity difference" concept; with h taken as $h_{1/2}$, $k_1 = 0.037$ in planar jets and $k_1 = 0.25$ in axisymmetric jets.
6	Schlichting	1942	$\epsilon = 0.0222\, u_e\, c_D d$ (Planar, incompressible)	Make of a cylinder of arbitrary cross section.

S. No.	Author/Model	Year	Expression for Eddy Viscosity	Remarks
7	Clauser	1956	$\epsilon = ku_e\delta^* = k\int_0^\infty \lvert u_e - u\rvert\, dy$	Applied to "wake"-like outer region of a boundary layer, $0.016 < k < 0.018$.
8	Hinze	1959	$\epsilon = 0.016\ u_e d$ (Planar, incompressible flows)	Wake of a circular cylinder.
9	Ting-Libby	1960	$\rho^2\epsilon = \frac{2\rho_c^2\epsilon_o}{y^2}\int_0^y \frac{\rho}{\rho_e}\, y'\, dy'$ (Axisymmetric, compressible)	ϵ_o is the constant density eddy viscosity and ρ_c is the center-line density.
10	Ting-Libby	1960	$\rho^2\epsilon = \rho_c^2\epsilon_o$ (Planar, compressible)	ϵ_o is the constant density eddy viscosity and ρ_c is the center-line density.
11	Ferri, et al.	1962	$\rho\epsilon = 0.025\ ((\rho u)_{max} - (\rho u)_{min})$ (Axisymmetric, compressible)	Extended Prendtl's third model to variable density, introduced "mass flow difference" concept.
12	Bloom & Steiger	1963	$\rho\epsilon = k\delta'\rho_c\ (u_{max} - u_{min})$ (Axisymmetric, compressible)	Attempt to extend Prendtl's third model to variable density, δ' is transformed wake radius.
13	Schetz	1963	$\rho^2\epsilon = 0.037\ \rho_c((\rho u)_{max} - (\rho u)_{min})$ (Planar, compressible)	Simple application of "mass flow difference" to planar flows.

S. No.	Author/Model	Year	Expression for Eddy Viscosity	Remarks
14	Alpinieri	1964	$\frac{\rho\epsilon}{\rho_j \epsilon_j} = 0.025\, h_{1/2} \left(\frac{\rho_c u_c}{\rho_j u_j} + \frac{\rho_e u_e^2}{\rho_j u_j^2} \right)$ (Axisymmetric, compressible)	
15	Zakkay, et al.	1964	$\epsilon = 0.011\, h_{1/2}\, u_c$ (Axisymmetric, compressible)	Presumes that centerline velocity and concentration decay is x^{-2}.
16	Donaldson & Grey	1966	$\rho\epsilon = \alpha \bar{k}\, r_{1/2}\, \rho \lvert u_o - u_e \rvert / 2$ (Axisymmetric, compressible)	Provides experimental data on Nitrogen and Methane.
17	Schetz	1968	$\rho\epsilon = k_s \pi (\rho_o u_o \delta_r^{*2}) / r_o$ where $\pi \rho_o u_o \delta_r^{*2} = \int_0^\infty \lvert \rho_o u_o - \rho u \rvert\, 2\pi y\, dy$ and $k_s \pi = 0.018$ (Turbulent eddy viscosity proportioned to mass flow defect (or excess) in the mixing region)	Unified Model.
18	Kinetic Energy			References 23, 24

of some available data for compressible jets. These calculations were made with the solution procedure of Reference 14 with several turbulence models. Previously the program was written with an explicit finite difference scheme but it was later modified to use an implicit/explicit finite difference scheme which resulted in more efficient computation. The program predicts gas dynamic, chemical and electrical properties of axisymmetric rocket plumes from sea level through the continuum flow regime.

Centerline velocity decay, spreading rate of jet and species concentration have been calculated. Some experimental results are available in references (23) and (25, 26, 6, 7, 8) for compressible jet-into-still Air, coaxial Air-Air mixing, coaxial Hydrogen-Air mixing (11), heated air and cooled air (6), Nitrogen, Methane (7) with which we can compare our results (Figure 1). While the nature of variation of centerline velocity looks in order, it does not give the expected type of variation. From the experimental results available it is anticipated that centerline velocity should decay by about 70% at around 40 radii but it is not happening in our case with any of the viscosity models used. The spreading rate is also not quite of the form as given by Warren (6). This further suggests the need of experimental as well as theoretical study.

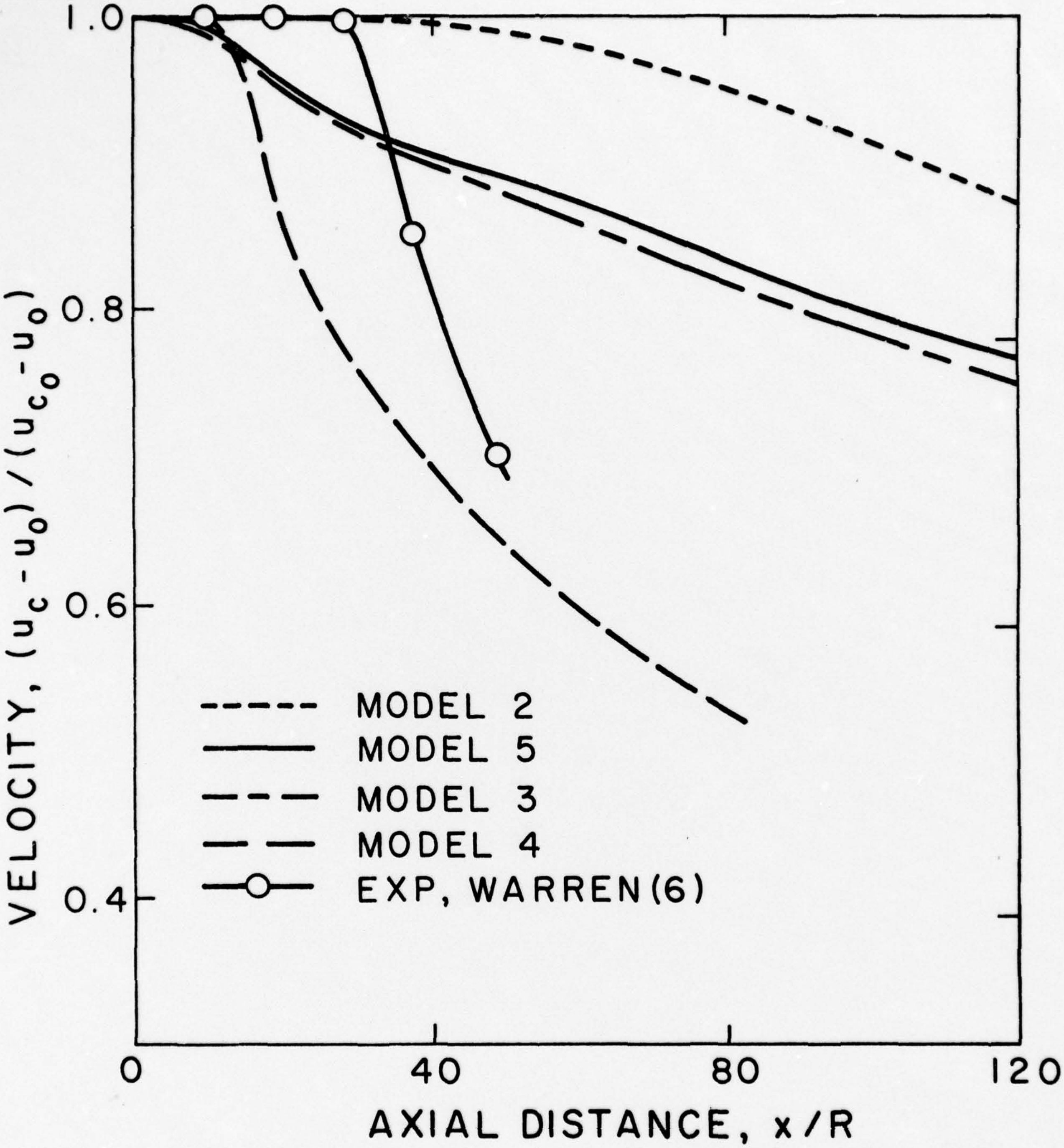

Figure 1. Calculated and experimental center-line velocity of a compressible axisymmetric jet. Turbulence models are taken from Ref. 14.

III. Particle Flows in Shear Layers

The presence of particles in exhaust plumes, particularly turbulent mixing regions, can contribute to design and prediction problems. Particles in the exhaust can contribute band radiation in excess of that characteristic of molecular radiation. The region of plume separation from the vehicle can further act as a flame-holder for the afterburning plume. This flameholding is sustained by shear layer reactions, including oxidation of carbon particles, rather than the recirculation zone created by the plume separation. The accurate overall description of the flow and reaction phenomena must consider particle/gas flow and reaction. Major unresolved difficulties persist in such a description. In addition to particle/gas mixing phenomena which determine initial temperature and velocity profiles at the nozzle exit, the description of particle formation and particle/gas reactions are little understood. The work which is reported here is an approach at analytical description of some of these phenomena.

The effects of particles in real gas flows are reflected in a number of changes in the flow. In general, particle velocity and temperature may be different from the gas velocity and temperature, the particles may diffuse at different rates in shear layers, and, finally, mass may be exchanged between the particle and the gas. Attempts to account for these effects have led to a number of approximate descriptions of the flow, Table II. Particle velocity and temperature have been assumed to be in equilibrium with the gas or frozen at its initial velocity or temperature. The same equilibrium or frozen description has been applied to particle diffusion effects and to phase change or chemical reaction of the particles. These two limiting conditions are most useful as extremes of the real, dynamic interactions between the two phases.

Table II. Particle properties relative to gas in two phase nozzle and exhaust flow.

	EQUILIBRIUM	KINETIC	FROZEN
VELOCITY	B	A,C,D,E	B
TEMPER.	B	C,D,E	B
DIFFUSION	G	A	
PHASE CHG.	G	E,G	

A present study
B Altman and Carter, 1956
C Kliegel and Nickerson, 1967
D Crowe and Pratt, 1972
E Jensen and Wilson, 1974
F Pergament, 1974
G Genovese et al., 1971

Table III. Characteristic data for exhaust plumes.

Gas Temperature, T_g	800 - 2500°K
Gas Pressure, P	0.1 - 1.0 atm
Gas Velocity, U_g	2.5 km/sec
Gas Density, ρ_g	2 - 6 x 10^{-4} gm/cc
Particle Denisty, ρ_p	2.0 gm/cc
Particle Size, d_p	.1 - 10 μm
Particle Loading	5 - 25%
Particle Re	10^{-3} - 10^{-4} $\lvert U_g - U_p \rvert$
Temperature Gradient	10^6 - 10^8 °K/sec
Velocity Gradient	10^8 - 10^9 cm/sec/sec
Transit Time	10^{-4} - 10^{-3} sec

A. Conservation Equations for a Multiphase Flow

The conservation equations for two-dimensional particle laden boundary layers can be written as follows (33):

Conservation of mass for carrier fluid including chemical reaction:

$$\frac{\partial \rho_f u_f}{\partial x} + \frac{\partial \rho_f v_f}{\partial y} = \Gamma \tag{1}$$

where Γ is the rate of conversion of particles to gas.

Conservation of mass for solid particles:

$$\frac{\partial \rho_p u_p}{\partial x} + \frac{\partial \rho_p v_p}{\partial y} = -\Gamma \tag{2}$$

Conservation of momentum for carrier fluid (neglecting the momentum due to generated gas):

$$u_f \frac{\partial u_f}{\partial x} + v_f \frac{\partial u_f}{\partial y} = -\frac{1}{\rho_f} \frac{d_p}{dx} + \nu \frac{\partial^2 u_f}{\partial x^2} + \frac{\rho_p}{\rho_f} + \frac{(u_p - u_f)}{\lambda_m} \tag{3}$$

where λ_m = particle velocity relaxation time = $\rho_p d_p^{\,2}/18\mu$.

Conservation of momentum in the axial direction for the particles:

$$u_p \frac{\partial u_p}{\partial x} + v_p \frac{\partial u_p}{\partial y} = \frac{u_p - u_f}{\lambda_m} \tag{4}$$

Conservation of momentum in the normal direction for the particles:

$$u_p \frac{\partial v_p}{\partial x} + v_p \frac{\partial v_p}{\partial y} = \frac{v_p - v_f}{\lambda_m} \tag{5}$$

Since the momentum transferred in the normal direction is small compared to that in the axial direction, Equation (5) will be neglected in the following analysis.

To describe analytically a suspension flow in a viscous layer, Equations (3) and (4), which are coupled, along with Equations (1) and (2),

which are also coupled, have to be solved simultaneously. A relationship exists between u_f and u_p, assuming that particle interactions are negligible and the relative turbulent drag is small, e.g. (33):

$$(u_f - u_p) = \left[\frac{.15g^{.17} d_p^{1.14} (\rho_p - \rho_f)^{.7}}{\rho_f^{.29} \mu_f^{.43}} \right] \qquad (6)$$

Where: d_p = diameter of solid particles

ρ_p = density of solid phase

ρ_f = density of gas phase

Substitution of this equation into Equation (3) yields:

$$u_f \frac{\partial u_f}{\partial x} + v_f \frac{\partial u_f}{\partial y} = d \qquad (7)$$

This equation differs from the equation of conservation of axial momentum for single phase flow only in the source term d where:

$$d = - \frac{1}{\rho u} \frac{dp}{dx}$$

for single phase flow, and

$$d = - \frac{1}{u_f} \left\{ \frac{1}{\rho_f} \frac{dp}{dx} + \frac{\rho_p}{\rho_f} + \left[\frac{.15g^{.71} d_p^{1.14} (\rho_p - \rho_f)^{.7}}{\rho_f^{.29} \mu_f^{.43}} \right] \frac{1}{\lambda m} \right\}$$

for two-phase flow.

This observation suggests that one way to solve the two-phase flow problem would be by modifying the source term in the solution procedures for one-phase flow and solving for the velocity of gas, then using equation (1) and solving for the velocity of the particle phase. The solution can be obtained by a modification of the integration algorithm developed by Patankar and Spalding (12) for 2D parabolic flow.

B. Calculated Results

The two-phase jet problem has been treated experimentally by Lewis (34) who measured axial and radial particle flow profiles at particle Reynolds numbers in the transition regime. Data were correlated in terms of decay of centerline particle flux, i.e.,

$$\frac{(\overline{uc})_{c\ell}}{(uc)_o} = \frac{A_o}{\pi c^2 x^2}$$

and radial profiles of particle flux

$$\frac{(\overline{uc})_r}{(uc)_{c\ell}} = \exp(-\frac{r^2}{ax})$$

The mean solid fluxes $\overline{uc}$ above are expressed in terms of an empirical constant $c = .0596$ and cross-sectional area A at different axial (x) and radial (r) locations.

As an illustration of the present analysis, calculations were made for the gas-solid mixture in Lewis' experiments and the required parameters needed for the Patankar-Spalding program were evaluated on that basis for different particle loading ratios. The program was modified for a jet and the initial conditions and the calculated properties of the gas/particle mixture were incorporated into it. The value used for the viscosity of the gas was that of air and far from the center-line of the jet it was set equal to twice that of air, because of higher rate of momentum transfer between the two phases in that region. Figures 2 and 3 show the results for different loading ratios.

The two-phase duct flow problem was treated experimentally by Doig and Roper (35), who measured the velocity of air as a function of radial distance for different axial distances in a duct of 1.7 inch inside diameter. Spherical particles were used with loading ratio ranging from .1

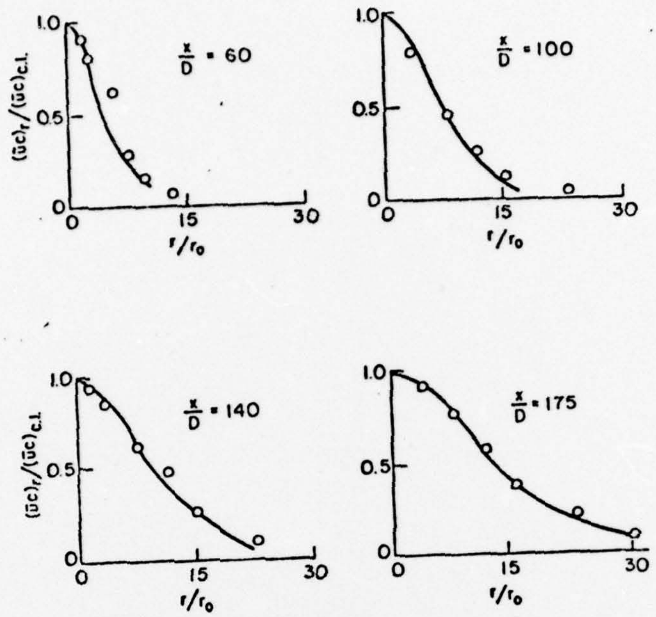

Figure 2. Calculated and experimental particle flux in a spreading two phase jet. Experimental data by Lewis(34) for low particle loading.

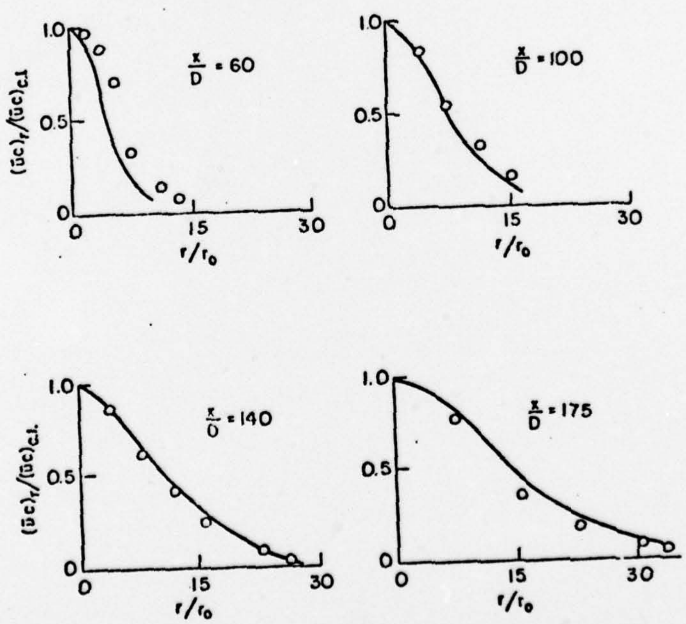

Figure 3. Calculated and experimental particle flux in a spreading two phase jet. Experimental data by Lewis(34) for moderate particle loading.

to 5.5. Data were plotted in terms of velocity versus square of relative distance from axis $(2r/D)^2$. The properties of the flow in the experiments were calculated for different loading ratios, Figures 4 and 5, for the turbulent transport properties determined by the jet flow calculation. In these calculations a mixing length turbulent viscosity was used for the gas:

$$u_t = \rho \ell^2 \left| \frac{\partial u}{\partial y} \right|$$

where $\ell = 0.09\ \delta$ and δ is the jet half width.

This rather simplified model for the two-phase jet and duct flow is seen to give generally close agreement to the experimental data. The results indicate the feasibility of the analysis as an approximation to two-phase flow in a parabolic boundary layer region of an exhaust flowfield.

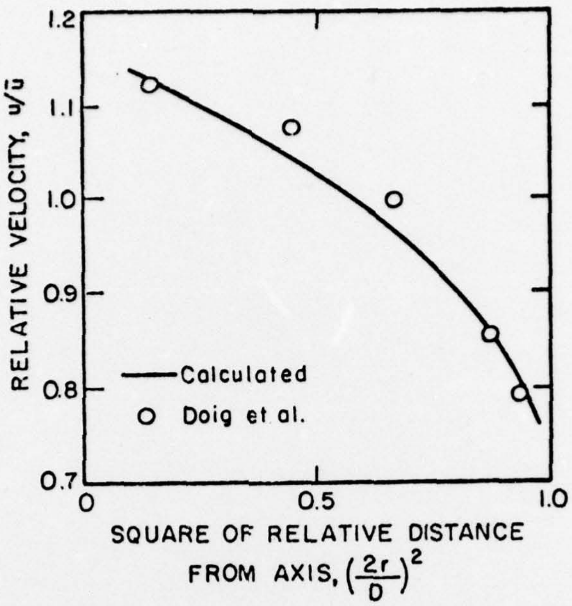

Figure 4. Velocity profile in core region of two phase duct flow with loading ratio of 3. Ref. (35).

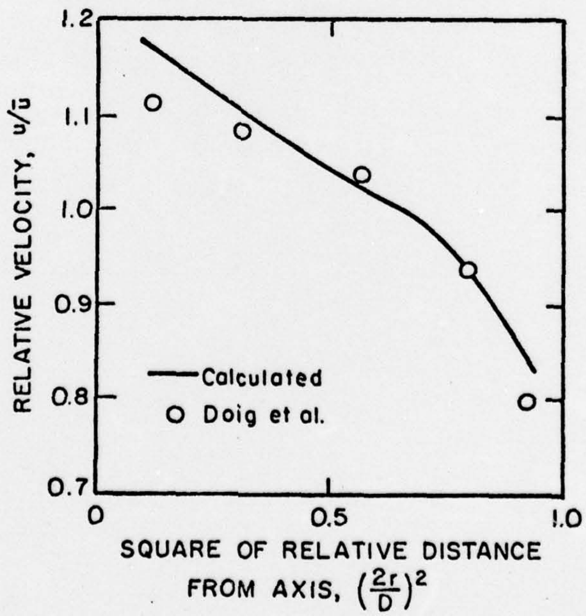

Figure 5. Velocity profile in core region of two phase duct flow with loading ratio of 4.4. Ref. (35).

IV. Chemical Nonequilibrium Effects in Shear Layers

Recent measurements by Ebeoglu, *et al.* (13) have indicated significant discrepancies between measured plume radiation characteristics and predictions based on the methods outlined above. Measurements of radiant intensity, spatial distribution of radiant intensity and plume radiation spectral distribution were made on a small kerosene/oxygen rocket. The measurements were then compared to predictions using a Naval Weapons Center plume prediction code and an Air Force Armament Laboratory code. It was found that neither code predicted the plume radiation characteristics with reasonable accuracy. At oxidizer/fuel ratios less than three the measured radiant intensity in the 4 to 4.5 μm band was as much as an order of magnitude greater than predicted (Figure 6). For O/F ratios greater than 4 the calculated radiation was twice that measured. Measurements of spectral distribution showed bands centered at 2.7 and 4.3 μm in agreement with predictions which considered CO_2 and H_2O as the dominant radiating species. However, the calculations predict less radiant intensity in the 4.3 μm band as compared to the 2.7 μm region. The measurement of spatial distribution of radiant intensity also showed disagreement between calculations and experiment. The peak radiant intensity was predicted to be much closer to the nozzle exit than was measured from the model rocket motor.

These results suggest serious deficiencies in the ability of state of the art computer codes to predict plume radiation properties. The discrepancies may arise from several calculational or experimental difficulties. The analysis above assumed combustion to chemical equilibrium products prior to expansion in the nozzle. Since the plume properties at the exit plane were not measured, the initial conditions for the

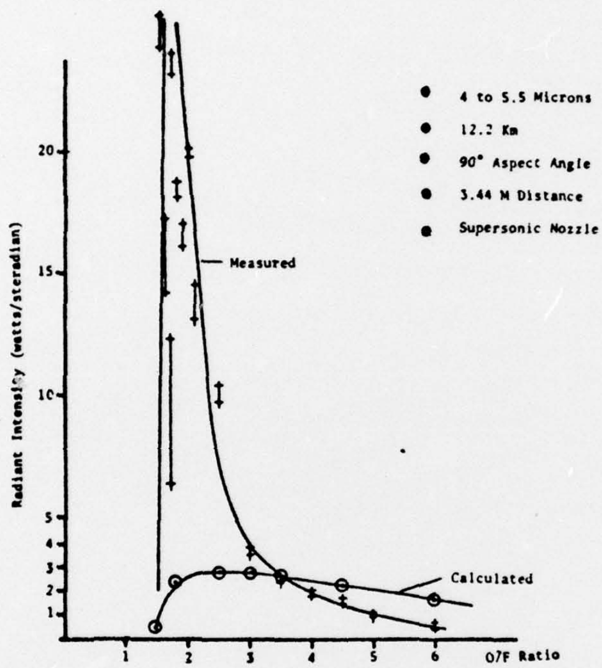

Figure 6. Variation of Radiant Intensity with O/F Ratio (Ref. 13)

afterburning plume were not known and should be determined. Separate calculations of nonequilibrium nozzle flow by Vamos, et al. (39) suggested that if equilibrium combustion is assumed, the nozzle exit concentration of CO_2 and H_2O are below equilibrium. Predictions based on these results would indicate lower initial radiation intensity. The possibility of an increased contribution to radiation intensity due to afterburning in excess of that calculated has been suggested (13).

In an attempt to describe the plume chemical characteristics and hence more accurately predict radiation properties, this study has focused on the exhaust plume initial composition. Calculation of the composition history in the exhaust plume has been made using the available chemical kinetic data and considering two composition initial profiles. In the first case the composition begins at the nozzle exit equilibrium composition and reacts as air is entrained into the jet. In the second case the composition at the nozzle exit is adjusted to simulate an excess of unburned fuel.

A. Calculated Results

The NASA CEC Computer program (36) was used to calculate the equilibrium combustion products in the chamber and exit plane. Calculations were made for a chamber pressure of 100 psia and initial temperature of 300°k. The principal constituents and their mole fractions are shown in Figure 7. Other minor species not shown in this figure, such as HCO, HO_2, O and H were predicted and included in the kinetic calculations. HCO is important in rich O/F ratios, while HO_2 appears only in the lean O/F ratio mixtures.

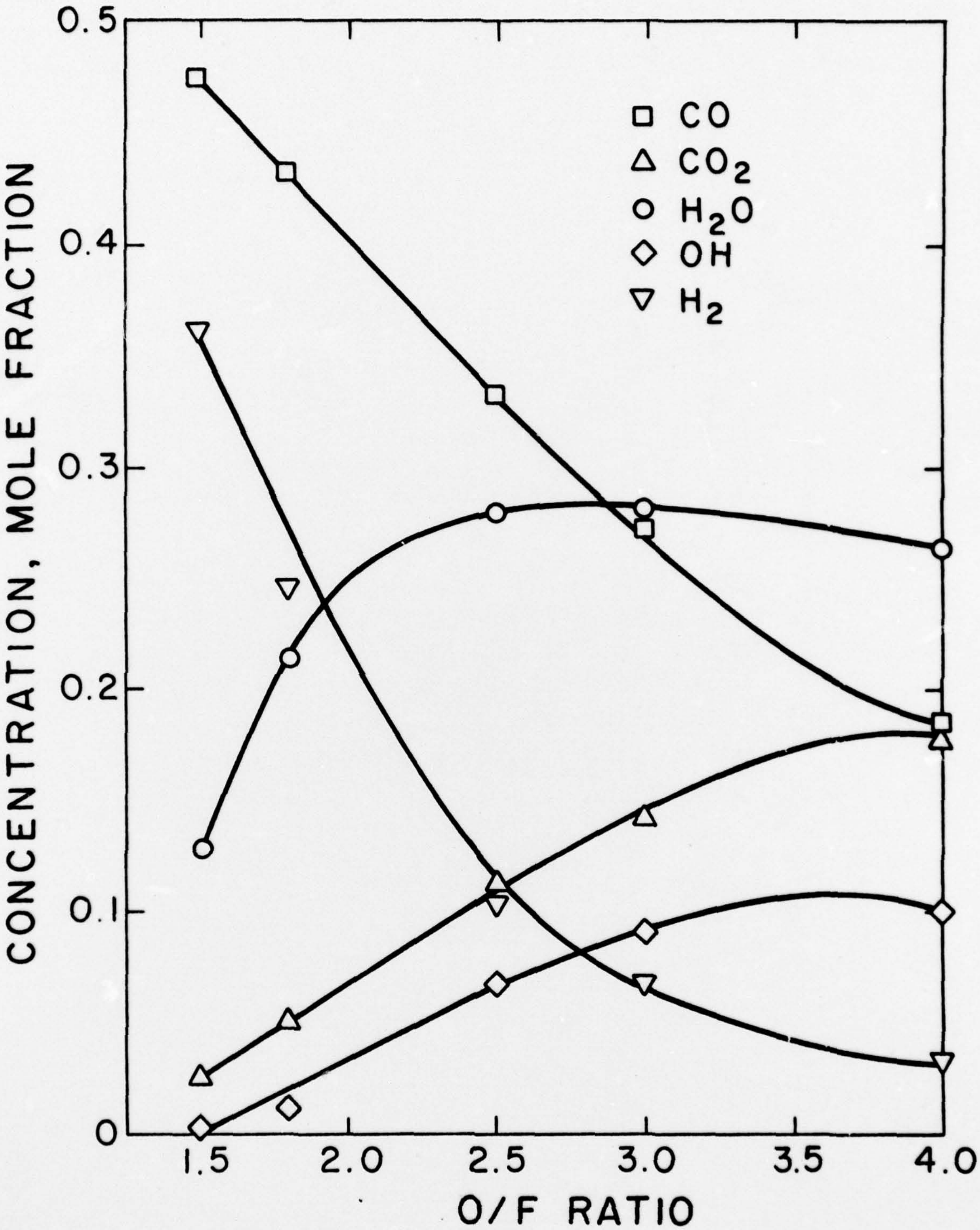

Figure 7. Equilibrium composition in the combustion chamber vs. chamber O/F ratio.

The fast computer program for nonequilibrium rocket plume predictions (1) has been used to compute the thermodynamic and chemical properties of a rocket exhaust plume. The rocket performance input data and chemical species concentration were given by the equilibrium calculations. The chemical kinetic data were obtained from references (2), (4) and (5) and are reproduced in Table IV. The same engine characteristics as those of (2) were used in these calculations.

The nonequilibrium chemical species concentration data used in this analysis were obtained by manipulating the equilibrium data. For example, 20% nonequilibrium condition was achieved by 20% increase in CO, O_2 and H_2 mole fraction and 20% decrease of CO_2 and H_2O from the equilibrium data obtained by NASA computer program. [Figure 7] The validity or accuracy of this assumption is limited, but qualitatively it follows the existing data.

B. Discussion

The primary results of the calculation are presented in Figures 8 and 9. In Figure 8 the axial variation of centerline concentration of CO_2 is plotted for several overall O/F ratios beginning with an equilibrium composition at the nozzle exit. At the most fuel rich mixture condition CO_2 increases very rapidly with axial distance which is similar to measurement of total radiation by Ebeoglu, et al. Concentration at low O/F was also found to exceed values at higher O/F by as much as a factor of two. If infrared radiation is taken to be primarily due to CO_2 and H_2O, this suggests an increase in radiation at low O/F ratios. Calculations for radial profiles comparing the equilibrium and nonequilibrium initial condition are given in Figure 9. These data show a further increase in CO_2 due to the nonequilibrium initial condition.

Table IV. Chemical Kinetic Data

	REACTIONS BEING CONSIDERED					KR=A*EXP(B/RT)/T**N A	N	B
1	O	+ O	+ M	= O2	+ M	.1000E-28	1.0	0.
2	O	+ H	+ M	= OH	+ M	.1000E-28	1.0	0.
3	H	+ H	+ M	= H2	+ M	.5000E-28	1.0	0.
4	H	+ OH	+ M	= H2O	+ M	.2000E-27	1.0	0.
5	CO	+ O	+ M	= CO2	+ M	.1000E-28	1.0	-2484.0
6	OH	+ H2		= H2O	+ H	.3600E-10	0.	-5167.0
7	O	+ H2		= OH	+ H	.2900E-10	0.	-9399.0
8	H	+ O2		= OH	+ O	.3700E-09	0.	-16692.0
9	CO	+ OH		= CO2	+ H	.9000E-12	0.	-1073.0
10	OH	+ OH		= H2O	+ O	.1000E-10	0.	-775.0
11	H2	+ O2		= OH	+ OH	.1600E-09	0.	-70400.0
12	CO2	+ O		= CO	+ O2	.3200E-08	0.	-54150.0
13	HCO	+ OH		= CO	+ H2O	.9000E-11	.5	0.
14	H	+ HO2		= OH	+ OH	.42 E-9	0.0	-19000.0
15	OH	+ HO2		= H2O	+ O2	.17 E-10	0.0	-1000.0

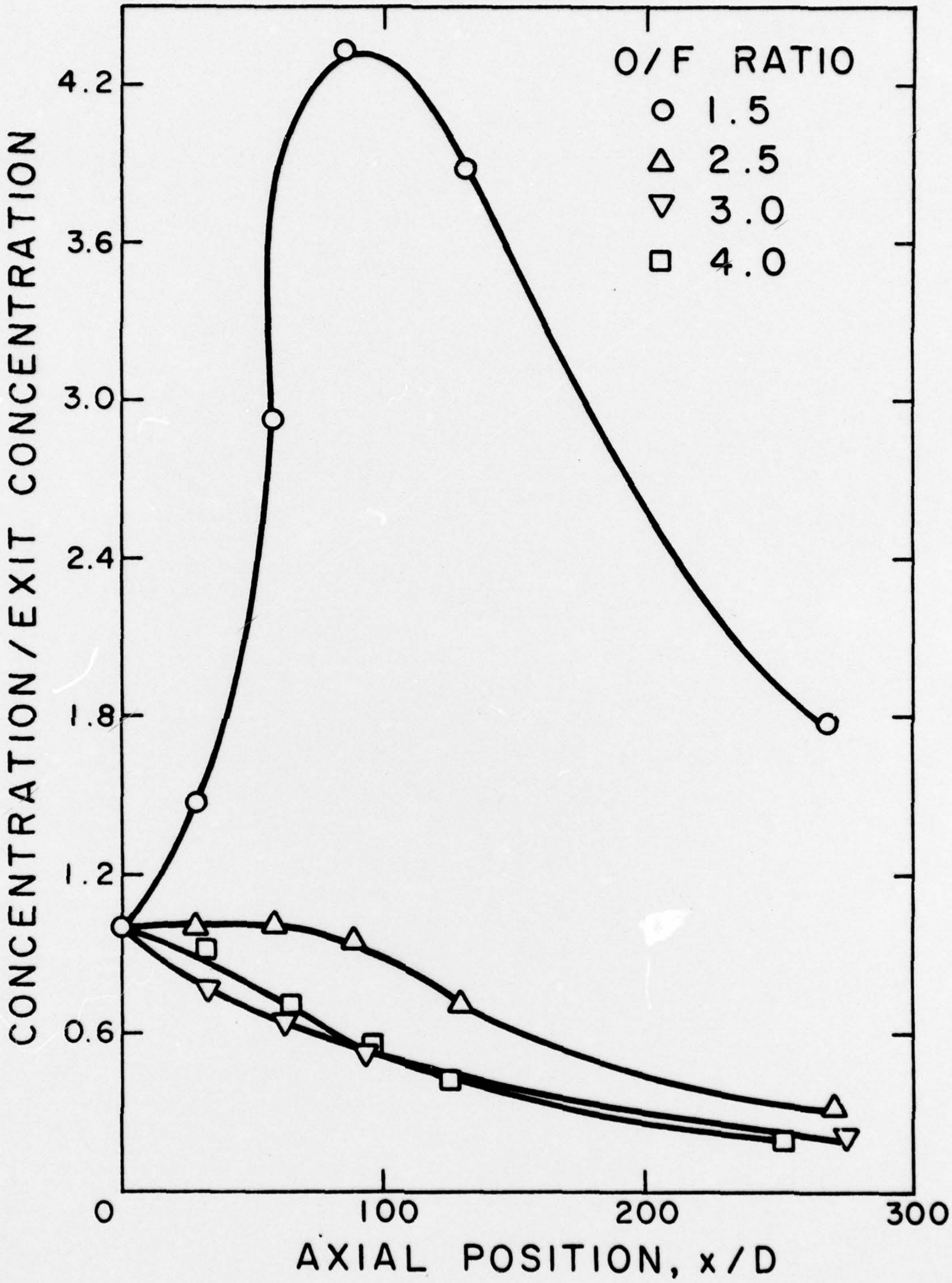

Figure 8. Axial variation of CO_2 concentration in axisymmetric jet plume at various O/F ratios.

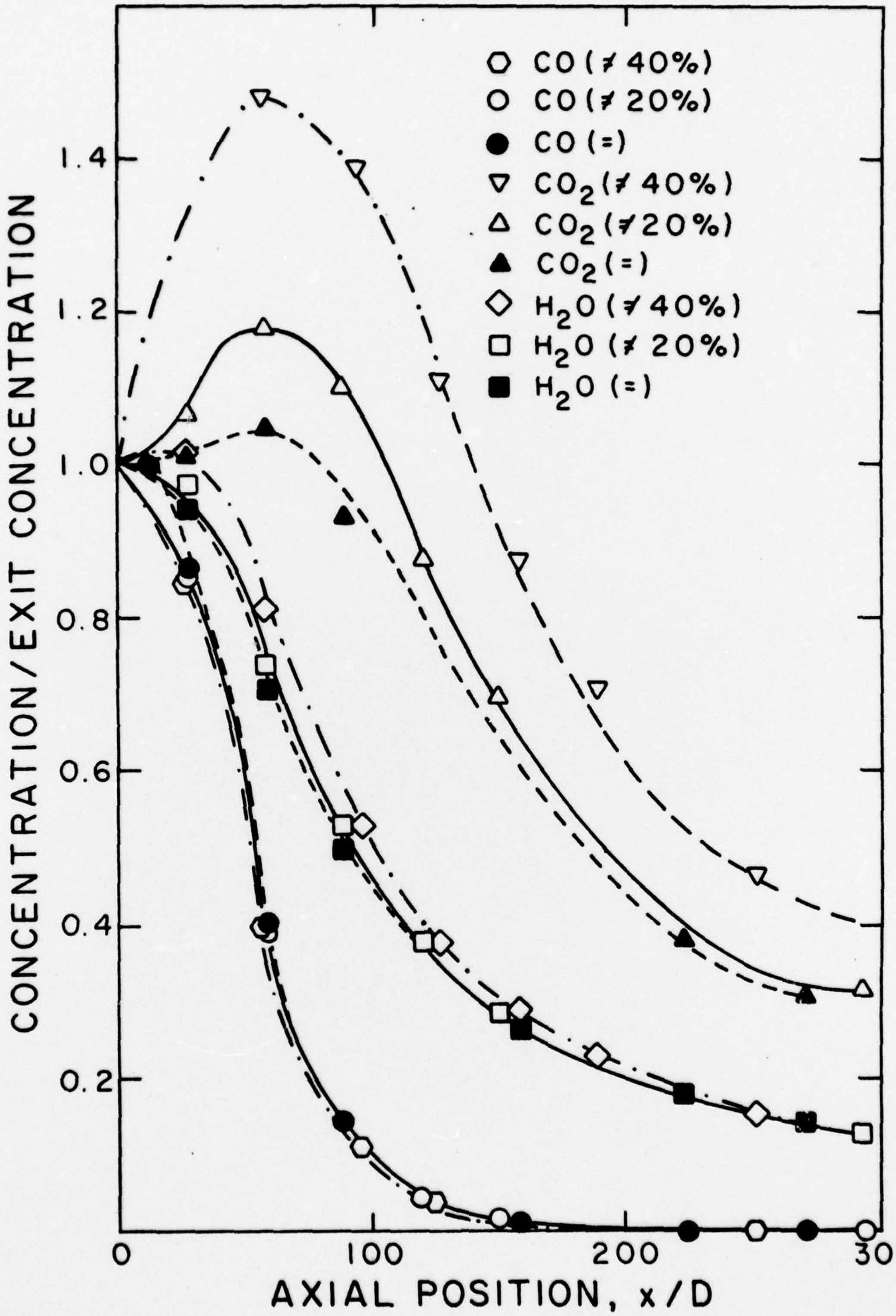

Figure 9. Comparison of centerline concentration profile for chemical equilibrium and nonequilibrium exit condition at O/F ratio of 2.5.

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